

Chapter Five

ACCEPTANCE CRITERIA OF DENTS

Acceptance criteria of dents, which is currently **only** based on the ratio of d/D , may need to be modified to include other parameters that **may** be influential in determining fatigue behavior. From the analysis of the experimental program and finite element **study**, results **from both** pipe and dent parameters affect the fatigue behavior of dents in pipelines. Dent parameters include dent depth d , dent **type**, and dent restraint. Dent **type** will involve the geometry and orientation of the **contact region**. Dent restraint can influence the rebound characteristics. Pipe parameters include diameter, thickness and grade.

Acceptance criteria for dents in petroleum pipelines should include input **from** both pipe and dent parameters. At the **time** of detection, the following should be determined:

- Dent depth
- **Shape** of the contact region of the dent
- Estimate of maximum pressure in pipeline after indentation
- Pipe diameter
- Thickness
- Restraint conditions of the dent

The dent depth recorded shall be the **maximum** found in the dented **region**. Typically, **this** will be located **at** the end of **the dent** contact region. The **shape** of **the contact** region gives an estimation of dent **type**. The **maximum** pressure after indentation shall be estimated for determination of rebound characteristics. The pipe diameter and thickness shall be determined from actual **measurements** or **documentation**. The finite element analysis **assumed** an uncorroded cross **section**. Corrosion can reduce the **wall** thickness and **seriously** affect the fatigue behavior of dents. Corrosion **can also** affect rebound behavior due to the reduced stiffness of the wall. Fatigue **crack** initiation may **occur** in locations of corrosion **in** dents.

At detection, the restraint of the dent shall be estimated. Excavation of a pipe to locate a dent will remove objects that may be restraining the dent. The restraint characteristics will change after excavation. Additional dent rebound may occur with pressurization after removal of dent restraints. The dent depth should be measured after pressurization such that the final residual dent depth for the dent is **known**.

With the input **parameters**, the fatigue behavior of the dent **can** be determined using the results of the finite element parametric analysis. Rebound behavior **can** be predicted using the Rebound Ratio. From **this**, the initial dent depth is estimated. The behavior of dents based on dent depth was presented based **on** initial dent depth in both the experimental program and the finite element parametric analysis. The mode of failure **can** be determined based on dent depth and dent **type** for the given pipe. The fatigue **strength** of a dent **can** be estimated by **knowing** the dent **type**, dent depth behavior, and failure mode. The initial dent depth is considered **as** a damage factor for determining fatigue **strength**. The fatigue **strength** is directly related to the failure **mode**. Dents with Mode 1 failure characteristics will have lower fatigue lives than dents with Mode 2 failure characteristics. Contact damage found in dents with Mode 1 failure **can** reduce the fatigue **strength**. Additional damage such **as** gouges in dents **can** further reduce the fatigue behavior.

Specific acceptance criteria **needs** be **based on** dent depth, dent **type**, and failure mode. Different dent **types** have **different** rebound behaviors **and** failure modes. Dents similar to **Type A** dents have more dent rebound than **Type BH** dents. The failure mode of **Type A** dents is more **severe** than for **Type BH** dents. Thus, the acceptable final residual dent depth for a **Type BH** dent will be larger than for a **Type A** dent.

Typical fatigue life **prediction** methods **are** not applicable for dents in pipes due to the changes in the dent geometry with changes in pressure. A deep dent **has a shorter** fatigue life than a shallow dent, but both **dents** will have similar **stress** ranges. An example is given in Fig. 4-72 for **Type A** dents of **different** depths where **all** of the dents have similar **stress** ranges. Thus, stress data **from** the finite element models cannot be directly used to predict fatigue behavior

based on stress range. Damage factors based on dent depth and failure mode are needed to estimate fatigue strength. The damage factors need to be correlated with actual failures found from experimental testing of dents.

As discussed previously, the AGA study resulted in the development of a method for fatigue life prediction based on d/D , D/t , pipe grade, mean pressure, and pressure variation. A stress concentration factor is determined based on these parameters. The stress concentration factor was set to be the ratio of change in stress over change in pressure, or $\Delta\sigma/\Delta p$. This stress concentration factor along with the pressure variation were used with the DOE-B curve to determine the fatigue life of a dent. The DOE-B curve is defined by:

$$N = 4.424 \cdot 10^{23} (\frac{\Delta\sigma}{\Delta p})^{-4} \quad \text{Eq. (5-1)}$$

where N represents the number of cycles until failure, $\Delta\sigma/\Delta p$ is the stress concentration factor, and Δp is the pressure variation. The fatigue life prediction using the DOE-B curve gave comparable results between the experimental dents tested and 2-D ring models. Results were only compared for the square flat dent profile which is similar to dent Type P.

The DOE-B curve was used to predict the fatigue life of dents from the current experimental program. This was done for Type A and BH unrestrained dents. Stress concentration factors were developed from the 3-D models presented in this study as well as the 2-D models previously developed. Stress concentrations used were based on the values at the mean pressure. Comparisons of predicted lives to actual lives of dents from the current experimental program are given in Table 5-1. In general, the predicted lives based on the 3-D models gave lower values than those from 2-D ring models. The predicted fatigue lives of Type A dents are mostly unconservative. The predicted lives of the Type BH dents are mostly conservative. This change is primarily caused by the change in failure mode between Type A and Type BH dents. Dent type was not used as a parameter for fatigue life prediction, which needs to be included based on the results of Table 5-1. The dent type was included in determining the fatigue life using the 3-D models. This method, like the results from the

previous research, does not accurately predict the fatigue life of dents.

Table 5-1: Comparison of predicted and actual fatigue lives of failed dents from the current experimental program.

Dent	Type	Actual	3-D Model	Fowier
1-A	A	94,559	312,016	1,579,579
1-B	A	33,521	14,498	47,306
1-C	A	27,031	22,813	90,623
3-D	BH	89,684	7,290	9,386
3-E	BH	80,880		9,386
6-E	A	21,541	81,571	1,779,696
6-F	A	8,349	30,600	1,779,696
6-G	A	11,791	18,738	1,779,696
6-H	A	3,785	11,307	856,304
9-A	A	12,711	12,143	1,557,742
9-B	A	30,108	148,798	936,018
9-C	A	18,608	23,837	1,637,102
10-B	BH	101,282	13,018	1,022,035

The stress concentration factor (SCF) is not constant for different pressures. A graph of SCF vs. pressure as a percent of the yield stress is given in Fig. 5-1 for unrestrained longitudinal Type A dents in Pipe 18-3. The SCF is defined as the ratio of the change in transverse stress over the change in membrane hoop stress. The SCF decreases with increasing pressure. It approached zero for the deeper dents with increasing pressure. At a high pressure, the stress is higher than the yield stress causing plastic flow. Additional pressure does not increase the stress level in the plastic zone resulting in the decrease of the SCF. Fatigue life prediction methods based on stress do not apply in this case. Strain behavior needs to be used instead since significant plasticity occurs during pressure cycling.

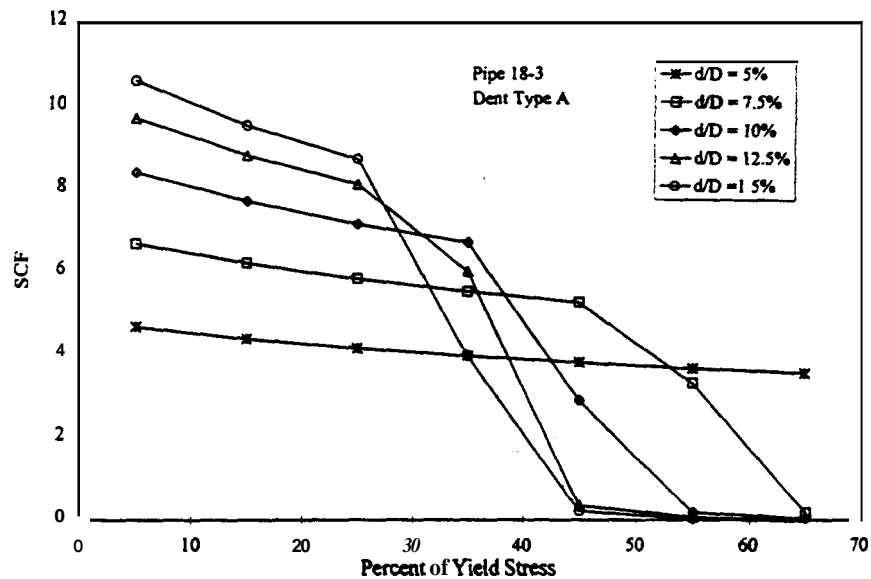


Figure 5-1: Stress concentration factors for **Type A** dents in Pipe 18-3.

Concentration factors based on strain are applicable for plastic behavior. A strain concentration factor (ϵCF) is defined as the change in transverse strain over the change in membrane hoop strain. A graph of ϵCF vs. pressure is given in Fig. 5-2 for **Type A** dents in Pipe 18-3. The ϵCF decreases with pressure similar to the SCF in the elastic range. The ϵCF increases significantly when the stress level passes the yield stress. For example, the ϵCF for the 10 percent d/D **Type A** dent given in Fig 5-2 changes from 6 to 14 with a pressure increase from 35 to 65 percent of the yield stress. The increase of the ϵCF occurs when the outside Surface transverse stress goes beyond the yield stress. The outside surface transverse stress distribution of the 10% d/D **Type A** in Pipe 18-3 is given in Fig. 4-66. The magnitude of the stress passes the yield stress between 20 and 40 percent of the yield pressure. Deeper dents have higher values of ϵCF at high pressures.

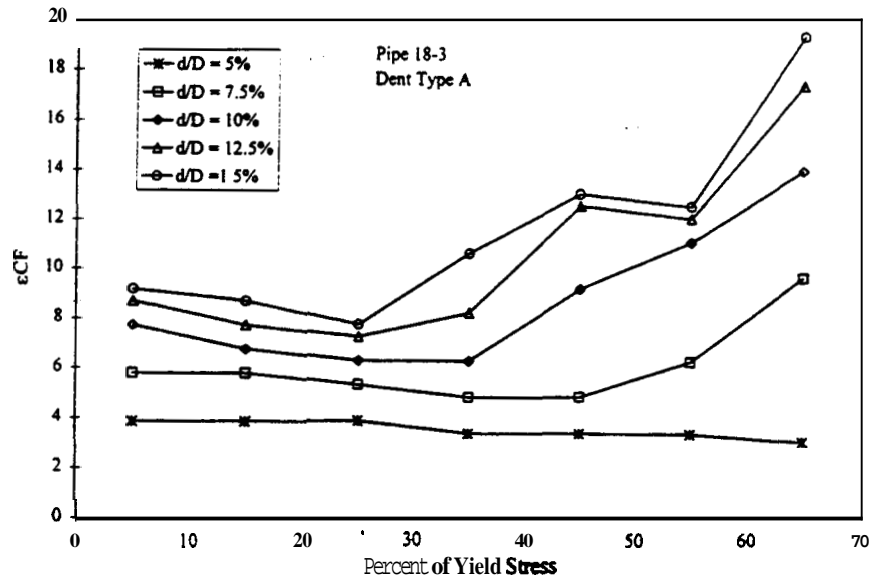


Figure 5-2: Strain concentration factors for Type A dents in Pipe 18-3.

Graphs of SCF and ϵCF are given in Figs. 5-3 and 5-4 for Type BH dents in Pipe 18-3. The concentration factors for stress and strain are considerably lower than for the Type A dents given in Figs 5-1 and 5-2. The ϵCF only increases for the two deepest depths at high pressures. This suggests that the two deepest Type BH dents have considerably lower fatigue lives when compared to the shallow Type BH dents. In the current experimental program, failures of Type BH dents only occurred for dents with initial depths of at least 10 percent d/D .

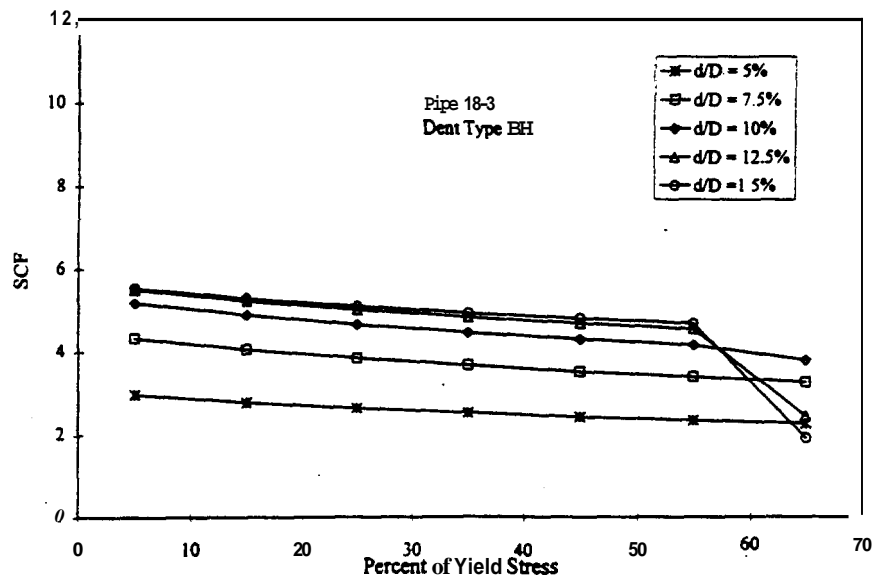


Figure 5-3: Stress Concentration Factors for Type BH Dents in Pipe 18-3.

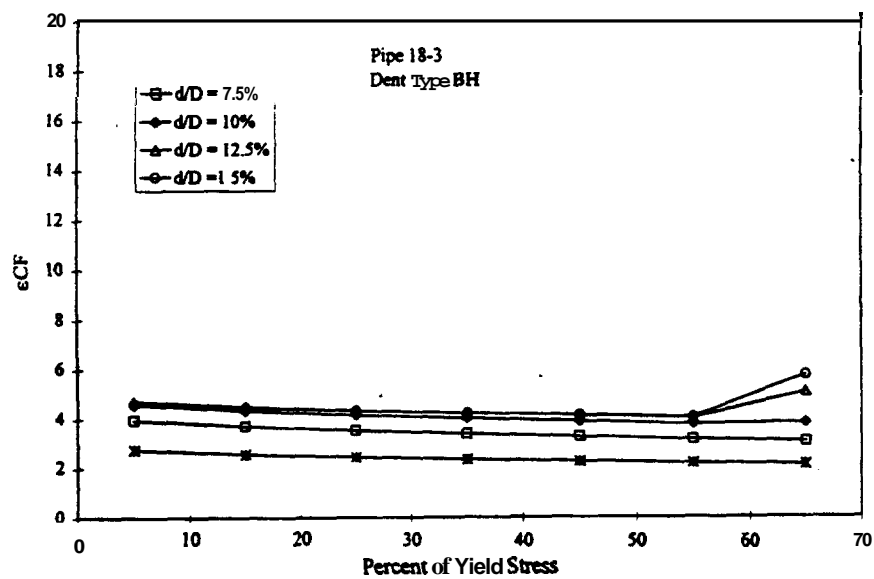


Figure 5-4: Strain Concentration Factors for Type BH Dents in Pipe 18-3.

Graphs of SCF and ϵ CF are given in Figs. 5-5 and 5-6 for longitudinal unrestrained Type G dents in Pipe 18-3. Both concentration factors for the Type G dents are similar to the factors for the Type BH dents. Type G dents have failure Mode 1 like Type A dents, but the concentration factors are lower. Thus, Type G dents will likely have longer fatigue lives than Type A dents.

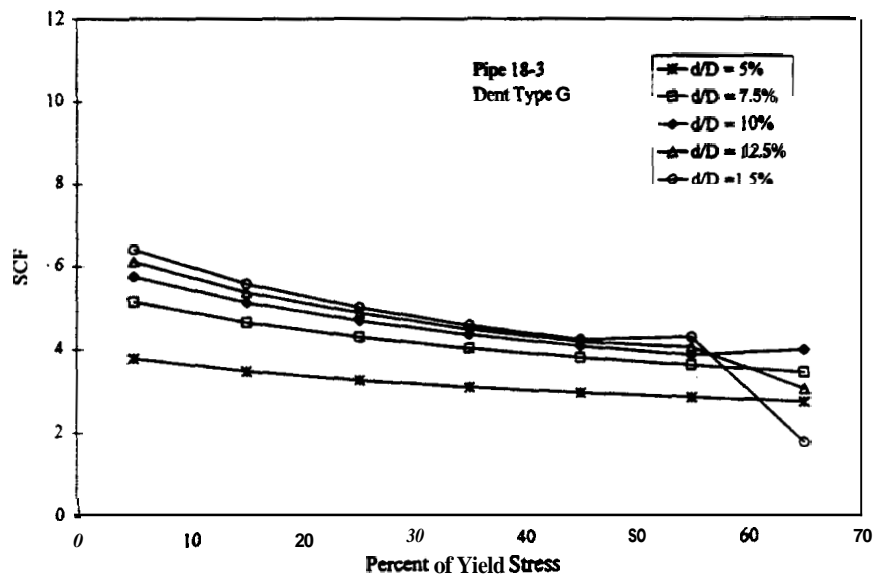


Figure 5-5: Stress concentration factors for Type G dents in Pipe 18-3.

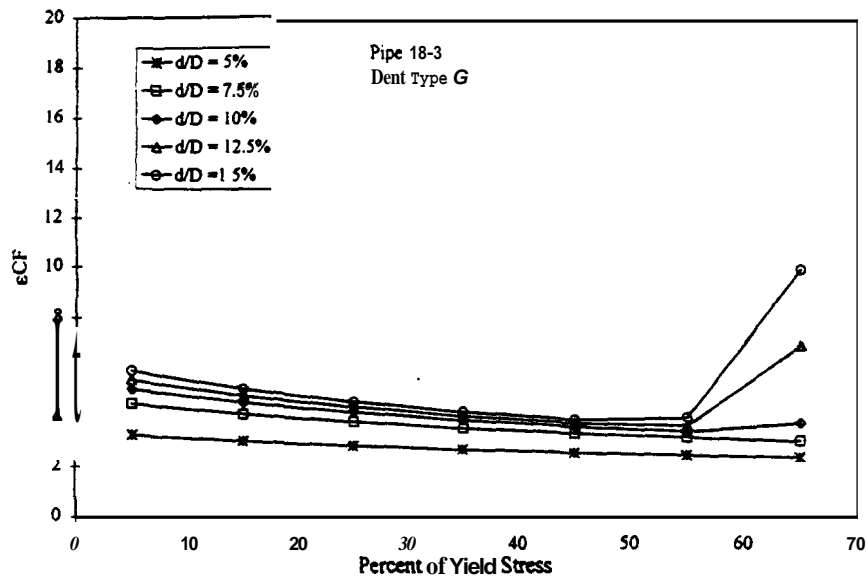


Figure 5-6: Strain concentration factors for Type G dents in Pipe 18-3.

Fatigue life prediction based on ϵ_{CF} was not performed, but conclusions drawn from the graphs of ϵ_{CF} suggest that fatigue prediction of dents based on strain is needed. Strain data can also be used to determine fatigue damage factors based on the rebound behavior. The change in strain through the stages of rebound is given for dent Types A, BH, and G for Pipe 18-3 in Fig. 5-7. The strains are given for the predicted failure locations. Strain data was recorded at the center of the dent for the dents of Type A and G. Data was recorded in the dent periphery for the Type BH dent. The Type G dents have the largest change in strain during rebound while Type BH dents have the lowest.

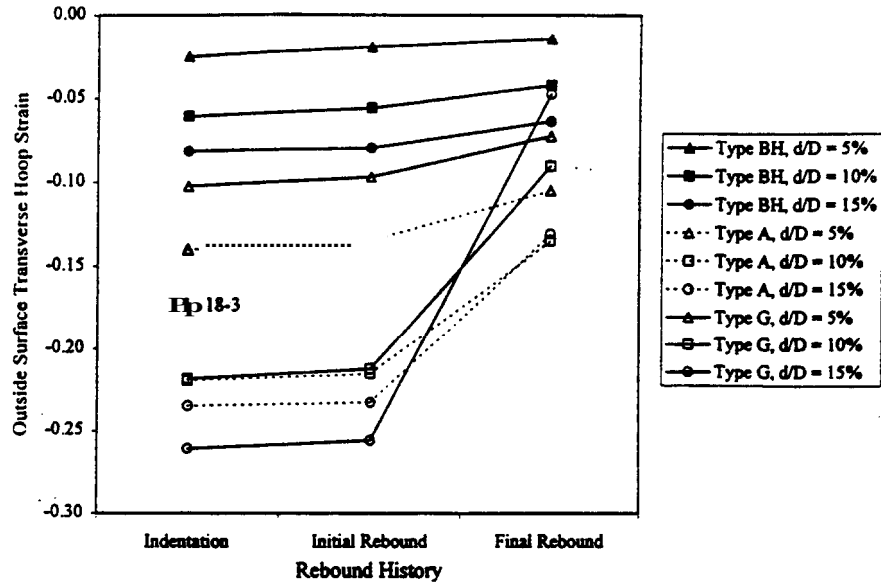


Figure 5-7: Strain history of dent Types A, BH, and G for Pipe 18-3.

A general procedure for determining dent *acceptance* is given in Figure 5-8. This method is based on the finite element parametric analysis. Results from the experimental test program can be used to calibrate the method.

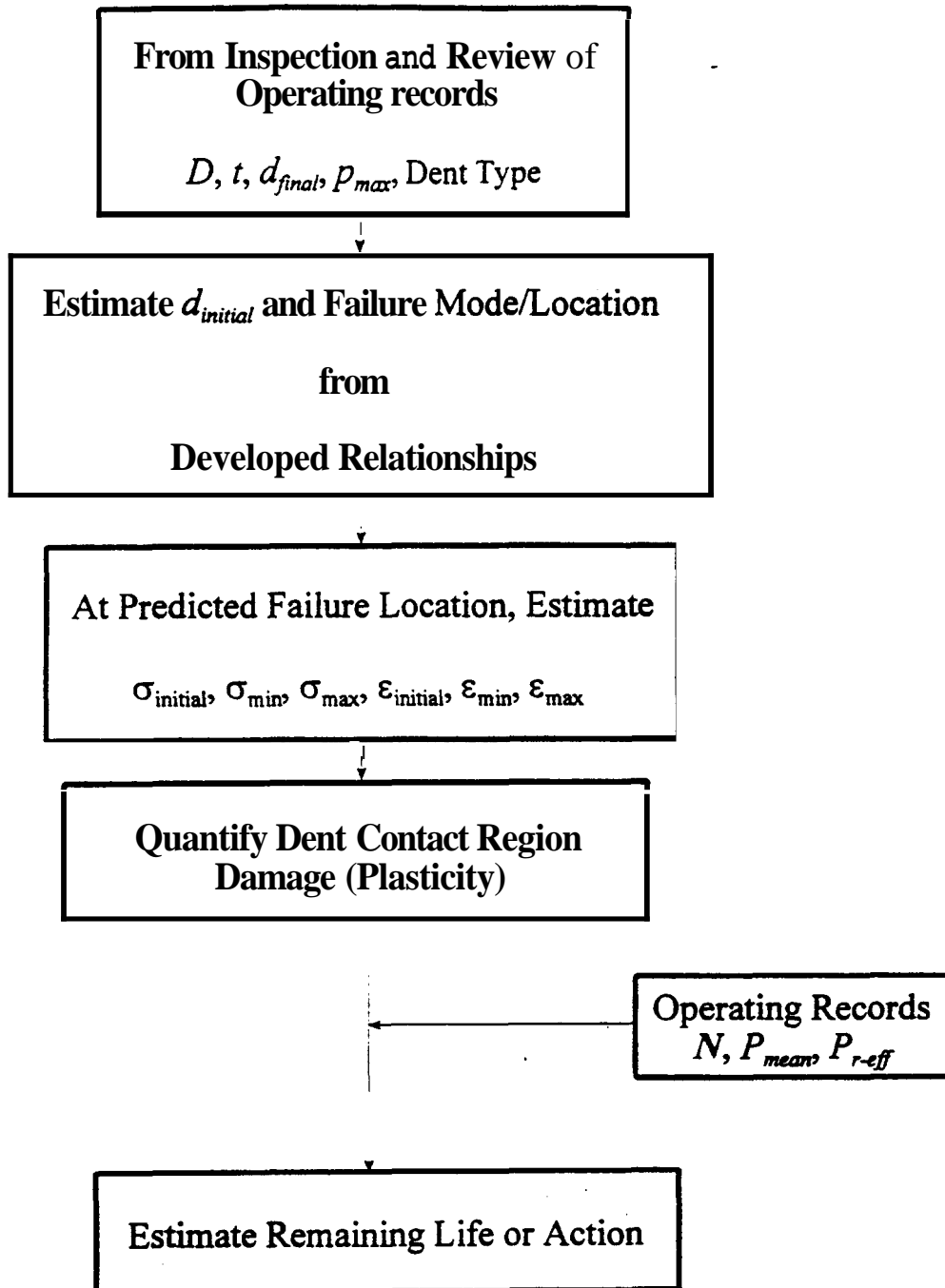


Figure 5-8: Dent acceptance procedure.

Chapter Six

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Through the analysis of experimental test data and finite element analysis, the following conclusions were reached with regard to the fatigue behavior of dented petroleum pipelines.

6.1.1 Rebound Behavior

The rebound behavior was found to be influenced by dent length, diameter, thickness, and pressure history. Longer dents have more rebound than shorter dents. Larger diameter pipes have more rebound than smaller pipes. Based on thickness, thin pipes have more rebound than thick pipes. An increase in pressure causes an increase in rebound.

From study of the rebound characteristics, a correlation was found between the initial dent depth at indentation to the final dent depth after rebound. For a given dent type in a given pipe, the ratio of final dent depth to initial dent depth remains constant regardless of initial dent depth. This ratio of final depth to initial depth is defined as the Rebound Ratio. The Rebound Ratio gives a simple method of predicting the initial dent depth for a dent found in a pipe that has undergone rebound from indenter removal and pressurization.

6.1.2 Stress Behavior

Stress data was studied to determine what locations in dented regions are susceptible to fatigue cracks. Fatigue cracks form on the outside surface in the longitudinal direction from the stress range of the outside surface transverse stress. In the dented region, the transverse stress is comprised of membrane and bending stresses, where the stress range at failure locations is dominated by the bending stress.

Two failure locations were found for unrestrained longitudinal dents. Long dents are susceptible to fatigue cracks inside the contact region. Shorter dent lengths are not susceptible to fatigue cracks inside the contact region. They develop fatigue cracks in the dent periphery; Fatigue failures that occur in the center of the dent are classified as Mode 1 failures. Failures found in the dent periphery are classified as Mode 2 failures. The mode of failure is primarily influenced by dent length. Other parameters that influence the mode of failure include diameter, thickness, and dent depth. Failure modes were predicted for different pipe sizes, dent lengths, and dent depths.

6.1.3 Restrained Dent Behavior

Restrained dents were found to have two failure modes consisting of either peripheral cracking or internal cracking under the contact region of spherical dents. Peripheral cracking of restrained dents is identical to Mode 2 failures of short dents. Internal cracks were found to be influenced by restraint flexibility. Internal cracks can develop on shallow restrained flexible spherical dents.

6.1.4 Acceptance Criteria

Parameters that can be used in determining acceptance criteria were found to include dent depth, dent type, pressure history, restraint conditions, and pipe parameters. From the parameters, the Rebound Ratio is used to predict rebound characteristics, and the failure mode is determined.

6.2 RECOMMENDATIONS FOR ADDITIONAL RESEARCH

Additional research is needed to increase the understanding of the fatigue behavior of dents in petroleum pipeline. This includes both experimental and analytical research. Experimental research should continue on dents not previously tested. This would insure that the fatigue behavior of all dent types has been examined. This would allow for the development of

comprehensive acceptance criteria. Additionally, local damage mechanisms from the denting process need to be studied more thoroughly. The initial defect **as well as** the resulting residual stress distributions around the dent govern fatigue behavior.

Further research in finite element modeling of dents will **also** result in improvement of the understanding of the behavior of dents in pipelines. Additional study of the data **from this** study **may** result in methods of **determining** damage factors to be applied to fatigue life prediction. **Strain** data **was** recorded for the models, but it **was** not studied. Investigation of the **strain** data may be applicable to the **determination** of damage factors.

A majority of the models in the current **study** are of longitudinal dents such **as** dent **Types A, BH, and G**. Other dent **types** should be modeled extensively. Additional models should be studied for transverse dents, spherical dents, and plate dents of various length and width. Only symmetric indenters were modeled oriented about the longitudinal and transverse directions. Some **unsymmetric** models should be investigated.

Shell elements were used to create the pipe mesh modeled. Shell elements do not allow for contact deformation of the thickness of the pipe. Modeling of the contact damage **can** be accomplished by **using** three dimensional solid elements in the contact region of the pipe mesh. Modeling of the contact damage will give **better results** of the **stress** behavior of the contact region.

Soil **interaction was** not modeled. **Unrestrained** dents were modeled without any restraint. **Soil backfill** will provide dent restraint during **pressure** cycling. A foundation system to simulate **soil interaction** should be modeled for the outside **surface** of the pipe.

The stress **data** from the models **was** higher than expected **as discussed** in **section 3.3**. The reason for the discrepancy **of the stress data was** not determined. It should be determined and corrected, if possible, before additional modeling.

Additional modeling of restrained dents should be performed. The methods of restraint modeled represent lower and upper bounds of restraint behavior. Different values of restraint flexibility should be modeled to get a better understanding of the behavior of restrained dents. The support condition used for the restrained dent models is not representative of support conditions of buried restrained dents.

The development of acceptance criteria of dents needs to be continued. The general method of determining new acceptance criteria of dents using rebound behavior and failure mode based on the modeling was discussed but not implemented.

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